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Ultrasonic Scanning System for Imaging Flaw Growth in Composites

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ULTRASONIC SCANNING SYSTEM FOR IMAGING
FLAW GROWTH IN COMPOSITES

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ABSTRACT

A unique system for measuring and visually representing damage in composite specimens while they are being loaded has recently been demonstrated at the NASA Lewis Research Center. It uses a hobbyist grade microcomputer system to control data taking and image processing. The system scans operator-selected regions of the specimen while it is under load in a tensile test machine and measures internal damage by the attenuation of a 2.5 MHz ultrasonic beam passed through the specimen. The microcomputer dynamically controls the position of ultrasonic transducers mounted on a two-axis motor-driven carriage. As many as 65,536 samples can be taken and filed on a floppy disk system in less than four minutes. As the specimen is scanned, a 16 level gray scale image is developed and displayed on a CRT. This image may be recalled later and can be enhanced in various ways or 'zoomed-in' on specific features. Many images may be stored in sequence as the load on the specimen is increased, and a movie showing flaw growth as a function of tensile loading can be generated.

INTRODUCTION

Multilayer fiber composite materials develop complex damage zones prior to fiber fracture. This damage principally consists of matrix cracking and interply delaminations. The determination of damage patterns is important in developing an understanding of the fracture process and to the subsequent development of a capability for prediction of the failure process. Initial predictions have been made but have not been fully verified experimentally.

A system was designed which could monitor the initiation and progression of local damage patterns in composite specimens under tensile loads. A fixture for holding composite specimens while they are immersed in a tank of propylene glycol and loaded by a 100,000 pound tensile test machine was developed and is shown in Figures 1 and 2. A scanning system to measure and display damage patterns as they develop during incremental loading was constructed using an 8080 based hobbyist grade microcomputer and miscellaneous equipment. Damage, as determined by the attenuation of ultrasound passed through the

specimen, can be displayed in real time in sixteen levels of gray on a CRT and stored as either single images or as a series of images.

The microcomputer system shown in Figure 3 was interfaced to a two-axis motor-driven carriage and an ultrasonic transducer signal conditioning system. The microcomputer controls and monitors carriage position. Selected areas of the composite specimen are scanned with focused-beam ultrasonic transducers mounted on the carriage. During data taking, the microcomputer continuously samples transducer output and processes the data for display. The sampled data can also be stored to a floppy disk and played back later with image enhancement. The goal is to use this system to develop 'motion' pictures of the flaw growth within the specimen as a function of the tensile loading.

The purpose of this paper is to describe the hardware and software systems which have been developed to make these measurements. The flaw growth research program for which the system will be used will be described by the system users at some later date. However, some preliminary results are briefly described to highlight various aspects of the design approach and to demonstrate some features of the system.

SYSTEM CONCEPT

Design objectives included a versatile low-cost system which could be easily used by non-programmers and could be readily interfaced to existing equipment. Other design objectives were: selective scanning of different regions of varying size and location on the specimen, CRT imaging of the scan data and control of its presentation, and post-test image processing and playback.

To meet these objectives a microcomputer system was chosen to control very general hardware interfaces, and software was used to perform most of the control and data processing. Most of the software is in 8080 assembly code and is generally invisible to the operator. The operator's interface to the system is through programs coded in the BASIC language. The operator simply runs the BASIC programs and answers a variety of questions posed by the system. Responses to

these questions set up operating modes for data taking and image presentation. These modes are communicated to the assembly coded routines by writing parameters to specific memory locations as part of the BASIC programming. When all of the control parameters have been set up in this way, the BASIC program calls the appropriate assembly coded routines which process and display the scan data. At the completion of a scanning operation, control returns to the calling BASIC program and the operator is asked how he would like to proceed.

Individual images generated by the scanning procedure consist of as many as 65,536 pixels in a 256 X 256 format. Data for these images are stored on a floppy disk as a set of normalized eight bit words for each pixel. All data from the two-axis motorized carriage and the ultrasonic transducer are taken with a twelve bit analog to digital converter and then normalized in various mode dependent ways to eight bit words. A short header consisting of test setup parameters which describe the test conditions is stored along with a continuous stream of transducer output data onto the floppy disk. Data taken from the potentiometers that measure carriage position are used only for control and are not stored. Five fully developed 65,536 pixel images can be stored on a disk.

The motorized carriage is positioned by lead-screw drive systems. A stepper motor horizontally positions the carriage, while a reversible direct current (DC) motor positions the carriage vertically. The motorized carriage is shown most clearly in Figure 5.

Data are taken during the vertical scans. After each vertical scan, the horizontal drive is stepped to the next scanning position. The data are generally taken bi-directionally with each stroke and return stroke of the DC motor driven carriage. The horizontal stepper indexes the carriage before the DC motor can reverse and scan the next vertical region. The speed of the overall data taking and imaging process is limited by the speed of the DC scanning drive. The vertical scanning is generally run as fast as possible considering the region to be scanned, the inertial loadings on the drive, the possibility of splashing the propylene glycol, and the limits on reversing currents generated by the DC motor controller.

Linear potentiometers on the horizontal and vertical drive carriages provide analog signals proportional to the carriage positions. These signals are multiplexed and digitized by an analog to digital converter. A horizontal drive measurement is made only at the start of a data taking sequence to center the horizontal drive in the region of interest. Then, operator-entered parameters are used to calculate how many steps the drive should make between vertical scans. The number of steps depends upon the size of the region to be examined, selected horizontal to vertical image scaling factors, and the number of vertical scans desired. After the number of steps is determined, the horizontal drive is positioned to its leftmost extent and the data

taking sequence is started. The horizontal drive then indexes the carriage from left to right until all of the data are taken.

As data are taken, the carriage vertical position is repeatedly measured with the analog to digital converter in an assembly code program loop. Once the carriage has reached a pre-defined sampling position, transducer data are taken, normalized, stored and then displayed on the CRT in accordance with chosen image presentation options. The next sampling position is then defined and, once again, the vertical carriage position is measured at a high rate in an assembly coded program loop until the new sampling position is reached. In this manner, 256 samples of the transducer output are taken and displayed for each vertical scan. Any non-linearities in the vertical drive motions, particularly due to high speeds and high accelerations are automatically compensated for in this manner.

Data taken during alternate up and down strokes are stored in memory as if the data were only taken during downward strokes. This is done for data storage consistency, since in two repeated tests, data for any particular vertical scan might be taken during either an upward or a downward stroke. Post-processing of the stored data is also much easier when the data are stored this way.

After the last sample in a vertical stroke, the DC drive reverses direction. Next, the horizontal drive is stepped to the next position. The position for the first sample on the next vertical stroke is defined and the data taking and display processing continue. This basic sequence is repeated until all of the required vertical scans are completed. Then, the motor control logic is disengaged, and both the horizontal and the vertical drive motors are returned to manual control.

Except for minor features, the playback of the recorded images uses basically the same imaging software as the data taking.

HARDWARE FEATURES

Figures 4 and 5 are pictures of the developmental hardware before it was mounted on the tensile test machine. The principal components are the microprocessor system, the ultrasonic signal conditioning system, the horizontal and vertical traversing carriage mounted within a tank of propylene glycol, and the specimen held in place by the lower grip assembly. The hardware and software systems were developed in this rig before installation on the 100,000 pound tensile test machine shown in Figure 1. Damage within the specimen is assessed by measuring the attenuation of ultrasound beamed through the specimen. The specimen is immersed in propylene glycol to provide good acoustic coupling with the ultrasonic transducers and to minimize corrosion of the metallic parts of the carriage and grip assemblies. A commercial piezoelectric transducer provides a focused 2.5 MHz ultrasonic beam. Best results were obtained with an unfocused receiving transducer to measure the

attenuation of the beam passing once through the specimen. Other operating modes include using the source transducer as the receiver as well. In this mode ultrasound passes through the specimen, reflects off of an inactive reflecting surface and passes back through the specimen to the receiver/transmitter. This mode has more sensitivity than needed for the composite specimens initially tested, but may be desirable with future specimens or other test configurations.

An ultrasonic signal conditioner and power supply provides excitation and conditions the output of the receiving transducer. The transmitter is pulsed on and off at an approximate rate of 16 KHz. The signal conditioner is synchronized with the transmitter pulse rate and a time gating circuit allows the operator to use only desired portions of the received signal. The gating eliminates signal returns due to multiple path reflections. The conditioner provides a continuous DC output proportional to the peak signal received in the time gate. This signal is sent to the microprocessor where it is digitized and displayed on the CRT.

The control microcomputer is based on the 8080A microprocessor with a 64 K byte random access memory and is designed with a standard S100 bus. A dual eight inch hard-sectored floppy disk drive is used. The default drive accesses operating software and the second drive stores or accesses transducer output. Each disk has a 384,000 byte storage capacity. The parallel output port of the control processor controls the motors of the horizontal and the vertical carriage positioning systems. The serial data port of the control processor interfaces to a line printer. A black and white video monitor displays both alphanumeric and graphics.

An analog-to-digital converter board was added on the S100 bus. The board has eight multiplexed analog input channels and a twelve bit resolution. The board was configured for a zero to ten volt operation with an unsigned binary magnitude digital output and for operation in a non-interrupt fashion. Status flags are monitored by the software to determine when a successful conversion has occurred. The twelve bit output word from the converter is reported to the system in two bytes. The most significant four bits of the most significant byte contain meaningless information and are always masked to zero by the operating software. The three channels used in this application are the outputs of the horizontal and the vertical drive potentiometers and the ultrasonic transducer.

Two video display boards were also added on the S100 bus. Some modifications were made to these boards and to the host system to allow for a full 256 by 256 pixel sixteen level gray scale output on the CRT. The video output of the microcomputer system was disconnected and mixed with the imaging video output so that the alphanumeric text generated by the processor and the imaged data could be displayed simultaneously. The two composite video signals were synchronized with a video phase locked loop. Other modifications were made on these and on system boards to adjust

for video signal polarities and to improve picture stability by intentionally adding some signal delays to portions of the combined video signals.

Two of the eight bits at the parallel output port control the horizontal carriage stepper. The carriage advances one step left or right depending upon which of the two bits are pulsed low. One or the other of the two control bits is latched low and a software timing loop is entered. After the required pulse width has been established, both of the horizontal drive control bits are reset high. The required dwell time between control pulses is then established by another software timing wait loop. Upon completion of this loop, more control steps can be taken by the system if required. Manual control of the horizontal drive is possible whenever the computer is not holding one of the control lines low.

Two other bits from the parallel output port control the vertical DC motor drive system. The DC motor speed is manually controlled by setting the armature voltage. Drive direction is determined by the armature supply polarity which is switched by relays. Transistor-transistor level logic is used in conjunction with the two control bits and two mechanical limit switches to control the armature relays. With both of the control bits held high or with the microprocessor in an unpowered state, the limit switches define the vertical scanning range and switch the armature relays accordingly. When one of the bits are held low, the drive moves either upward or downward depending upon which bit is being controlled. The mechanical limit switches override the control bits if a conflict occurs.

The mechanical limits of the vertical carriage can readily be adjusted to suit a given specimen mounting configuration. The limits are measured by the software before the microcomputer takes control of the vertical drive. This is done during an auto-ranging process for transducer output normalization, as well as to assure that the operator desired vertical extents are within a feasible range.

SOFTWARE FEATURES

The hardware interfaces were designed to be as general as possible, and software provides the majority of the control and signal processing functions. The software was designed for easy use by a non-programming operator. The operator engages the software through BASIC language routines which set up and check operating parameters and then call assembly language routines to do the control and data processing. The operator needs only to type either 'BASIC SCAN' or 'BASIC VIEW' to start scanning a specimen or to play back stored data. After that, various conditions are reported to the operator who responds by answering questions which the program asks. The answers set up the required data taking and image processing functions.

Defaults, provided in the BASIC language programs, can readily be edited to provide a

starting set up for a given test sequence. The operator can change any of the default parameters during his question/answer session in a 'global' mode or in a 'selective' mode. In the 'global' mode, the operator is asked to define all of the parameters in a question/answer sequence. In the 'selective' mode, the operator changes individual parameters one at a time in a question/answer sequence. A parameter changed during an operating session retains its changed value as the new default. Each parameter is checked for consistency with physical constraints on the process. For example, the desired horizontal motor drive extents are calculated from the operator inputs. These extents are then checked to assure that the operator has not inadvertently asked the system to drive the horizontal carriage into the tank walls. Other constraints, such as the feasible extents of the vertical carriage drive are measured by operating the scanning drive between mechanical limit switches before the software can take control of the drive. If any default parameter is inconsistent with the physical system, the operator is asked to re-define that parameter.

Once the horizontal center of the feature to be scanned has been defined and checked, an assembly-coded routine is called to step the horizontal drive to that position and to cycle the DC motor between its mechanical limits. The limiting values from the vertical potentiometers define the feasible motor drive extents. The maximum DC output from the ultrasonic signal conditioner is also recorded. Control then returns to the BASIC routine which calculates a normalizing factor for the transducer output so that the full range of the available signal is used for imaging.

Next, the number of vertical scans to make is entered as a number from 2 to 256 and a contrast enhancement index is defined.

The contrast enhancement index is used to limit the number of gray scale levels that the system uses for imaging. This strongly demarks areas of transition when representing damaged areas. A sixteen level gray scale image can be presented in eight, four or two levels (black and white) using this index. A white scale shift index is also used which doubles the image brightness a number of times so that the 'brightest' range of data produces a fully white display. These two parameters provide the image enhancement options for data taken in real time or played back from the floppy disk.

Next, a horizontal scaling factor is defined. Normally this parameter is set to one. If it is changed, the horizontal or vertical dimension of the scan is compressed to fill the screen. This allows differing damage areas to be 'squashed' to fit the screen dimensions. This factor, the starting position, and the number of scans required determines the ultimate limits that the horizontal drive carriage will be required to traverse. If the calculated limits are beyond a feasible range, the operator is requested to change one or more of these parameters.

A zoom index is also defined for magnifying some region of the image to be displayed. Individual pixels are scaled to many times their normal size in accordance with the zoom index. Zoom coordinates define the center region to be zoomed in on in terms of the screen coordinates for an otherwise un-zoomed image. Even though a zoomed image is displayed during data taking, a full un-zoomed image is stored on the disk.

When very small regions are scanned, a problem with signal latency may occur due to propagation time in the propylene glycol and averaging time taken by the conditioner. On alternate up and down strokes of the carriage an occasional stair-stepping of the image with scan direction has been observed. This occurs during faster traversal rates when scanning small regions. The effect is particularly noticed at sharp edges such as the damage-initiation slots machined in the composite specimens. In order to minimize this effect a 'slow scanning' mode can be selected so that data are taken only during the downward strokes. In this way, all of the signal latency at the sharp edges is in phase for adjacent vertical scans and the stair-stepping in the resulting image is greatly reduced.

When all of the parameters are defined, they are copied into the assembly code data tables which remain in core memory with the BASIC calling routine. The playback of stored data works the same way but fewer operator parameters are copied into memory. When all parameters have been transferred, the BASIC routine calls the assembly coded routines which take and process data.

The assembly routine first calculates a table of vertical positions at which transducer data should be taken. The table has 256 sixteen bit entries; each entry is four times the required sampling position coordinate. Next, the program determines which way the drive is going and checks to see whether the carriage is beyond the extent of the sampling position tables. When the carriage is unambiguously beyond either of the sampling table limits, the computer takes control of the DC drive, reverses its direction, and begins taking image data.

During data taking, the vertical carriage position is continuously measured and each sample is stored sequentially in a four word circular buffer. After each sample, the four words in the buffer are added and compared to the sampling position word pointed to in the sampling position table (The summed values tend to average out any noise in the sampled carriage position). If the drive is going up and the sum is greater than or equal to the sampling position value, the transducer output is sampled. Conversely, if the drive is going downward and the sum is less than the sampling position value, the transducer output is sampled. The transducer data is then left shifted in accordance with the normalization index, and stored in a temporary buffer. The transducer data is manipulated in accordance with the contrast index and whitescale shift provisions, and the resulting four display bits (corresponding with the sixteen possible gray levels) are written to the appropriate screen

buffer address. The program then checks the sampling position table pointer index to see if the last data was the last required for the scan. If not, the pointer index is updated, a new sampling position is defined and the program again measures the vertical position continuously until the next sampling position is crossed.

After the last sample of a vertical scan, the horizontal address for the on-screen display pixels is updated and the set of sampled data from the vertical scan are written to a disk write buffer. Data is written to disk if the disk buffer completely fills during this operation. The horizontal drive is stepped a predetermined number of steps and the DC motor drive direction is reversed. The scan counter is updated and checked. If there are more scans to do, the data taking proceeds with the return stroke of the vertical drive using a routine which indexes the opposite way through the sampling position value table. If the slow-scanning option was selected, a different routine repositions the drive beyond the other end of the sampling position table and reverses the vertical drive. The normal data taking routines for a downward stroke are then called which enables the data taking procedure to continue.

When all of the vertical scans are completed the remaining data in the disk write buffer is written to the disk and the disk file is closed, if the disk write option was selected. Next, the horizontal and vertical drive control bits are disabled to allow manual control. Program control then returns to the calling BASIC routine and the operator is asked if he wants to quit, change the defaults, or make another scan with current defaults. During incremental load testing on the tensile test machine the tensile load is increased between scans.

APPLICATION EXAMPLES

The system provides a qualitative picture on a CRT of the graduated internal damage of specimens which is impossible to see in other ways. The pictures give interesting results which tend to agree with our notions of the internal structure of the specimens and seem to show expected damage patterns for certain kinds of loadings. During one early series of system development tests, pen point indentations were seen on the specimen surface due to its prior use as a hard surface for writing.

While very high sensitivity has been obtained in some cases, no quantitative correlations have been made between the signal attenuation and the actual damage of the specimens. That is part of the planned research which will be done using this system in conjunction with analytical code development and detailed specimen examinations.

Figure 6 shows local damage in a broken graphite epoxy specimen which was scanned as part of the system development. The physical region shown in the photograph is about 1 1/2 by 3 inches. The broken surface of the specimen is not visible in

the figure but is shown in phantom. Notice the regions of apparent progressive damage shown by the graduated tones in the photograph. Also, note how extensive the damage is below the break line and the asymmetries of the damage pattern. The bright region to the right appears to have experienced little damage while the region in the center appears to have experienced extensive damage.

Figure 7 is a scan of a 3/8 by 3/4 inch region around a sharp edged notch in an otherwise undamaged fiberglass epoxy panel. The dark region around the notched hole is due to local damage around the hole and possibly some signal scattering of the focused sound beam at the sharp edges around the hole. Notice the two slanted lines running vertically through the image with the darker region in between. These lines are aligned with one of the interior plies and may show overlap or missing filaments in that ply. The darker region between the lines may be due to some internal bonding problems. These images cannot be interpreted exactly. However, their presentation seems to be in agreement with the internal geometry and structure of the specimen.

This is also true for Figure 8 which represents a 3 by 5 inch region of an undamaged graphite epoxy specimen and appears to show some matrix effects. The lines in the pattern match the known fiber orientations of the plies.

Figures 9, 10 and 11 are the same view of the same broken specimen displayed in a sixteen levels of gray, eight levels, and four levels respectively. The damage initiation slot is near the top center of these figures. A pair of dark areas which corresponds with local delamination before the specimen broke can be seen around the slot. These areas look like a pair of bracketing 'parentheses' and qualitatively agree with initial analytical predictions. The 'parenthesis' on the right is partially obscured by a broader area of damage which apparently occurred when the specimen broke. Note the progressively sharper demarcation of the damage as the number of gray levels was reduced in Figures 9 through 11. The authors feel that, for this particular specimen, the eight level gray scale image gives the clearest overall picture of specimen damage without removing significant midrange detail.

Figures 12 through 16 are from a checkout test sequence with a specimen being incrementally loaded by the tensile test machine. Damaged areas can be seen to grow as the tensile loading is increased beyond 11000 pounds. Figures 17 and 18 are a 'before' and 'after' image of the overall specimen. The imaged sequence clearly shows the way in which damage grows about the damage initiation slot.

Unfortunately, for this test setup, a clearly demarked graduated damage indicated by midrange gray tones, was not observed. In order that this initial test sequence be taken under constant conditions, the transducer settings were not changed as the testing proceeded. The initial set up of the transducers for a given test series

will have to be determined empirically for the types of test specimens to be run. This will be one of the considerations for the future work done with this instrument.

SUMMARY AND CONCLUSIONS

A hobbyist grade microcomputer system was interfaced to an ultrasonic transducer signal conditioning system and a motor driven X-Y scanning carriage. All interfaces were made very general, with assembly level coding accomplishing most of the control and data taking operations. The operator uses BASIC language routines in a question-answer fashion to set up operating parameters and to initiate measurements. Image enhancement software options are available for both real time display and for playback of stored data from the disk.

It is possible to monitor and to image the internal damage in a composite specimen with this instrument while the specimen is being loaded in a tensile test machine. Further, it is possible to record a series of images which illustrate progressive damage with increasing load on the specimen. The correlate well with anticipated damage patterns, with graduated images showing different levels of internal damage within the specimen, as well as otherwise unseen details of the internal structure of the specimen.

Future use of this instrument will be directed toward correlating experimental results with analytical predictions of the internal damage of tensile loaded composite specimens.

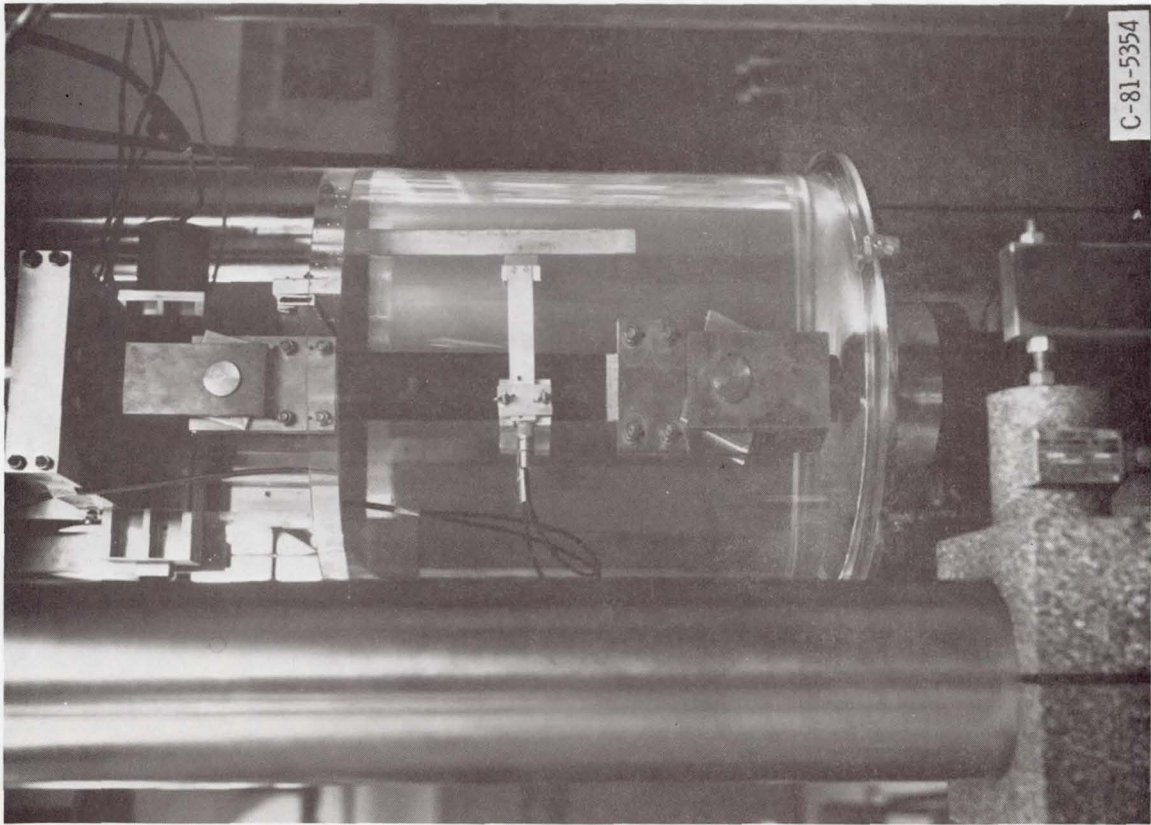


Figure 1. - Composite specimen mounted in the tensile test machine.

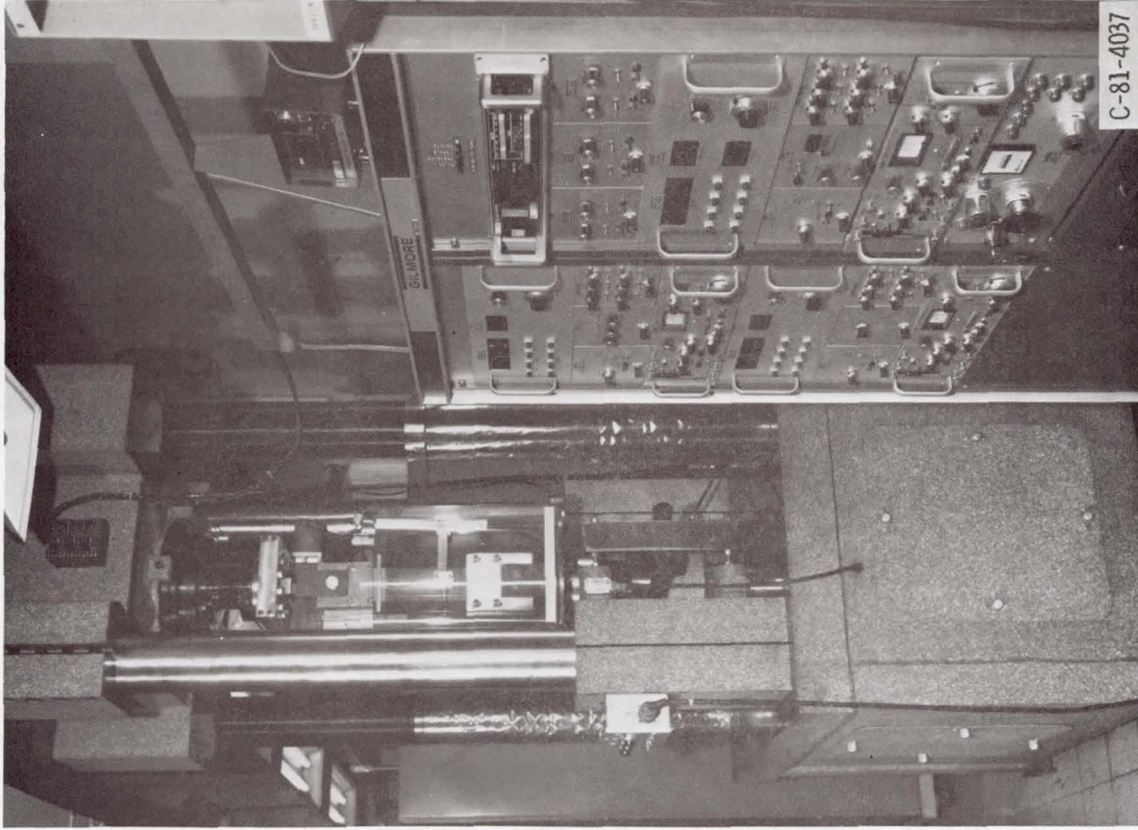


Figure 2. - 100 000 pound tensile test machine.



Figure 3. - Microcomputer system.

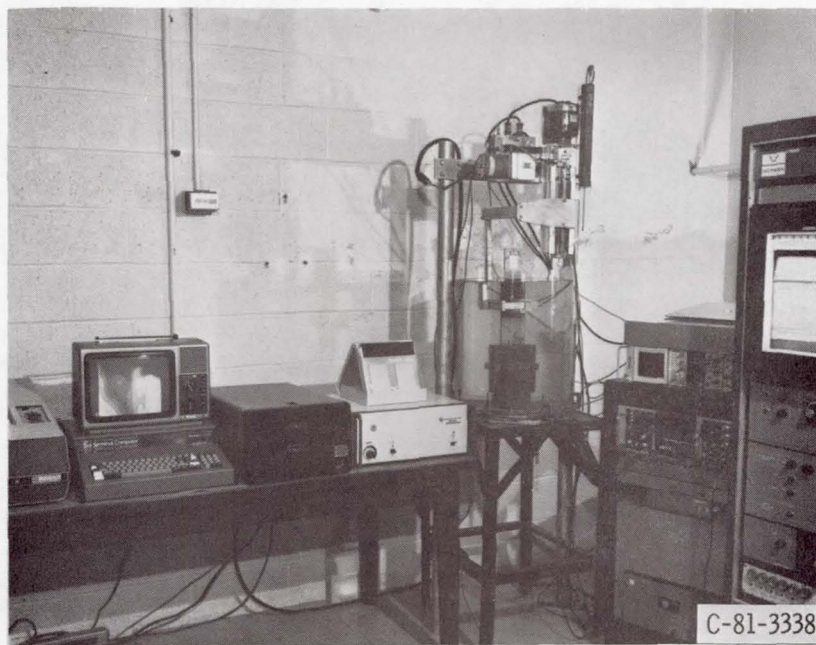


Figure 4. - Developmental hardware.

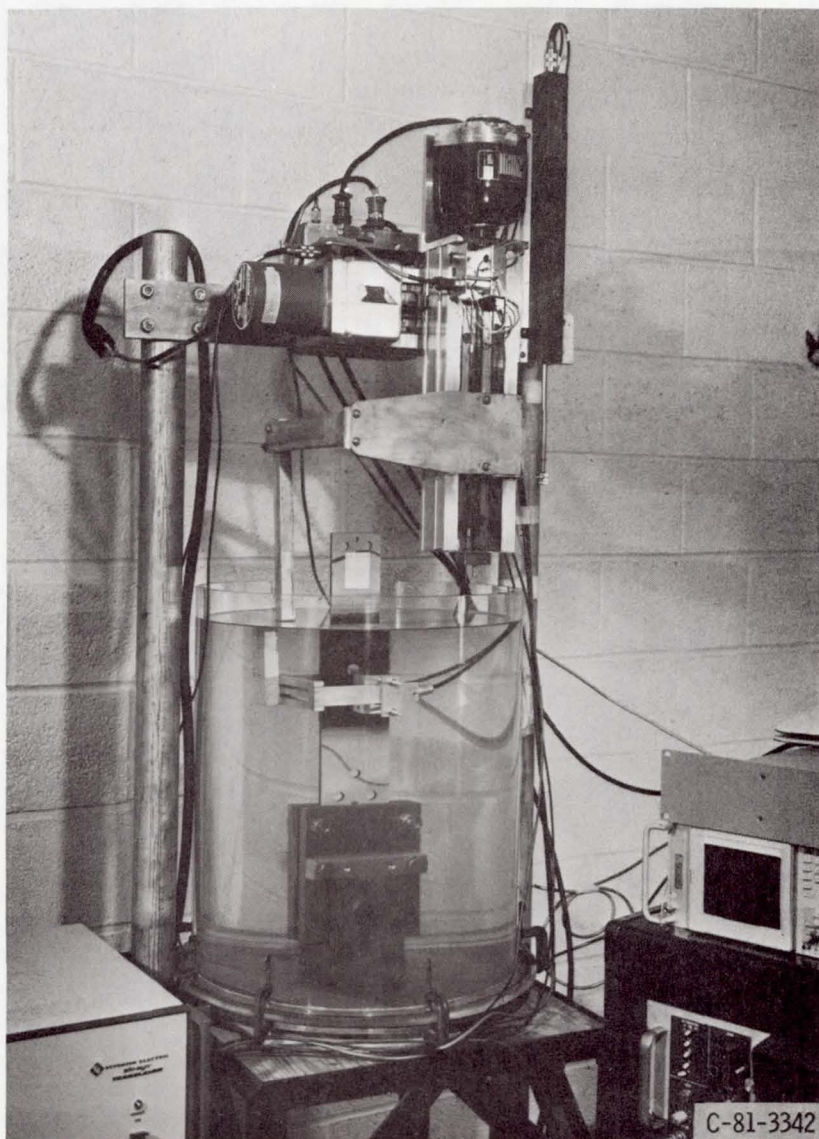


Figure 5. - Motor driven scanning carriage.



Figure 6. - Imaged damage in a 1 1/2 x 3 inch area of a broken composite specimen.

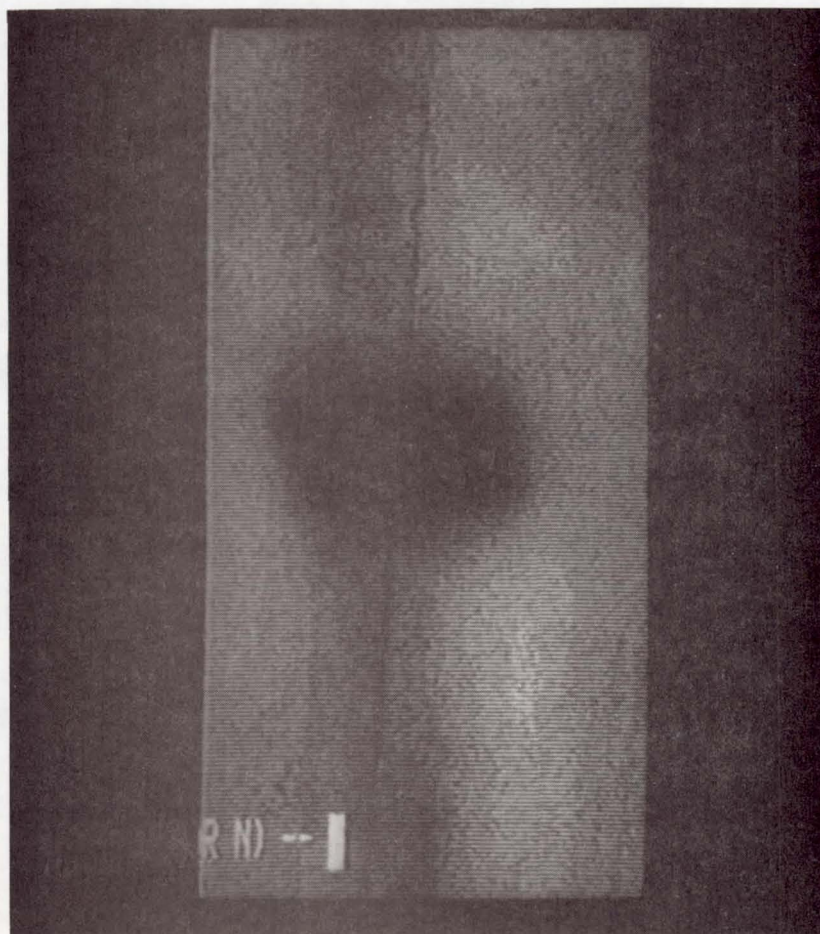


Figure 7. - Image of a 3/8 x 3/4 inch region about a hole in a composite panel.

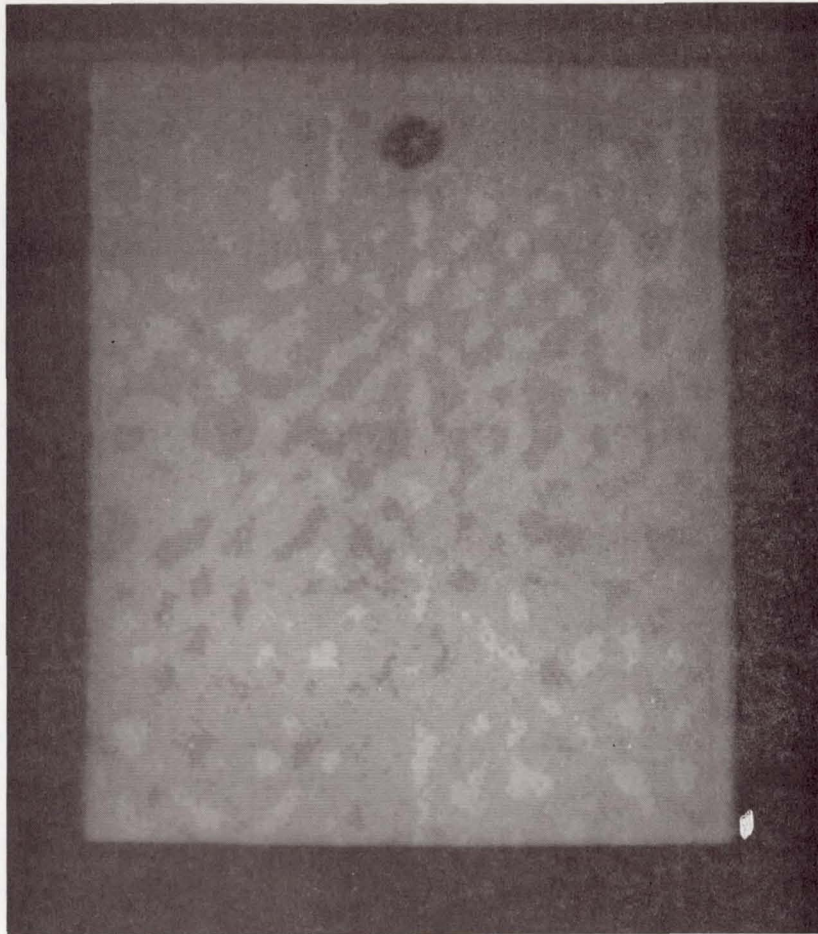


Figure 8. - Image of a 3x5 inch area of an undamaged graphite epoxy specimen.



Figure 9. - Sixteen level gray scale image of a broken composite specimen.



Figure 10. - Eight level gray scale image of a broken composite specimen.



Figure 11. - Four level gray scale image of a broken composite specimen.

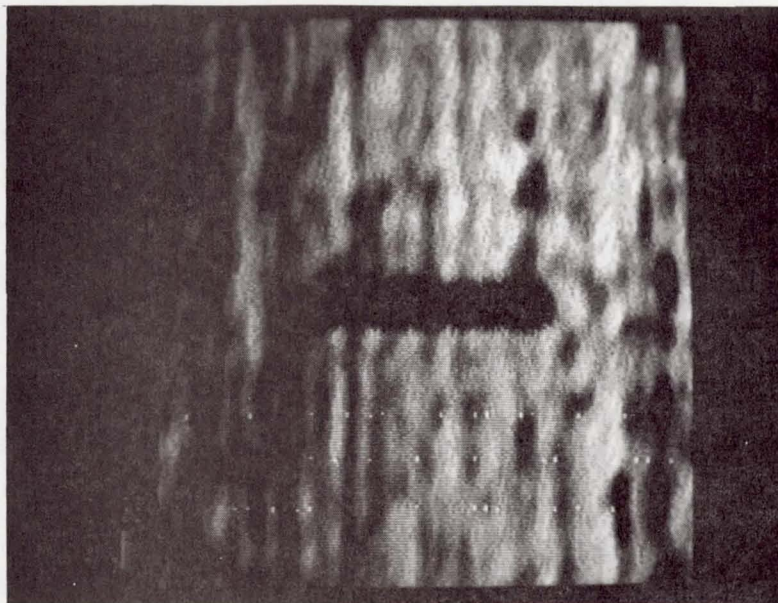


Figure 12. - Tensile loaded specimen: 0 pounds.

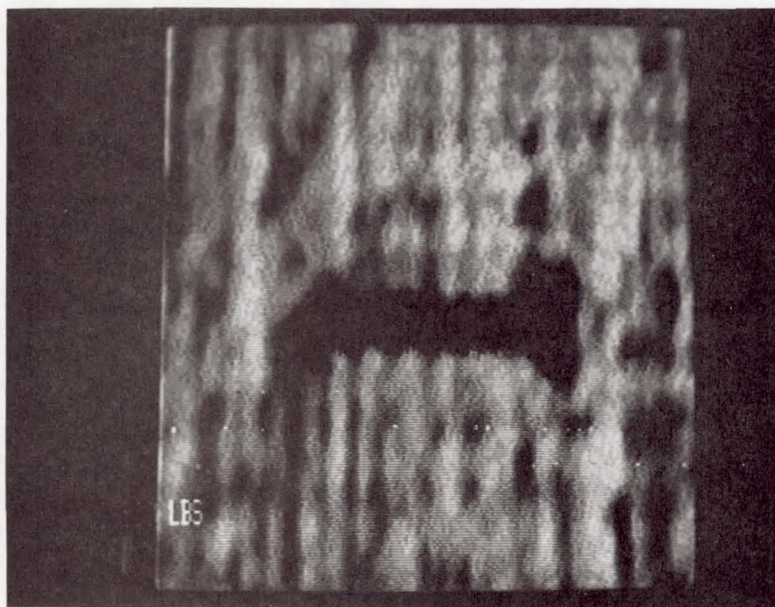


Figure 13. - Tensile loaded specimen: 11 800 pounds.

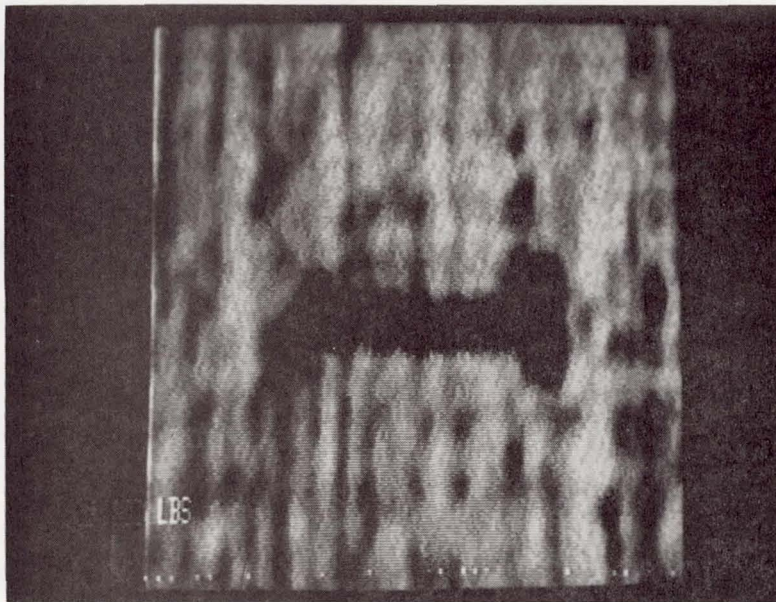


Figure 14. - Tensile loaded specimen: 12 100 pounds.

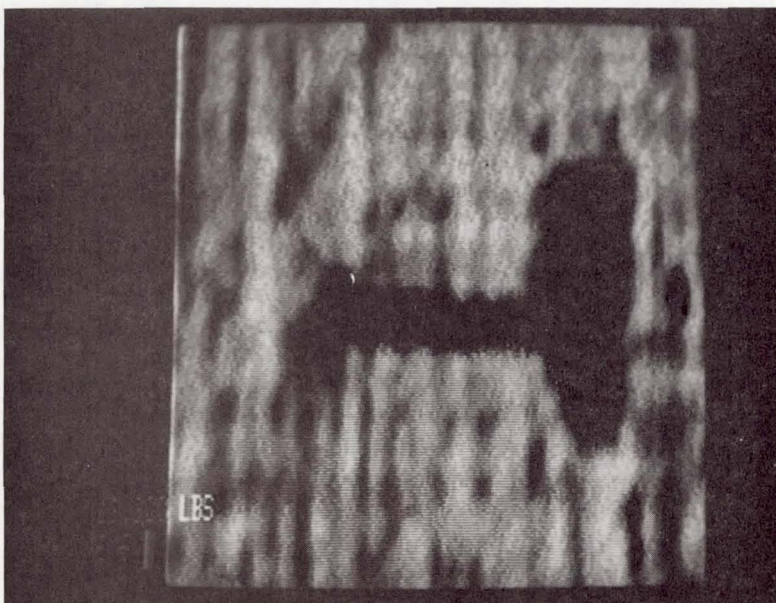


Figure 15. - Tensile loaded specimen: 12 200 pounds.

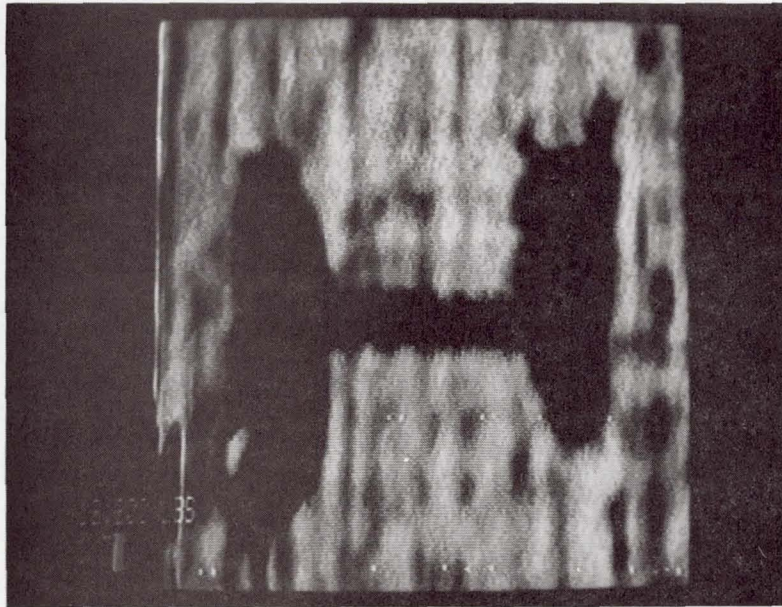


Figure 16. - Tensile loaded specimen; 12 350 pounds.

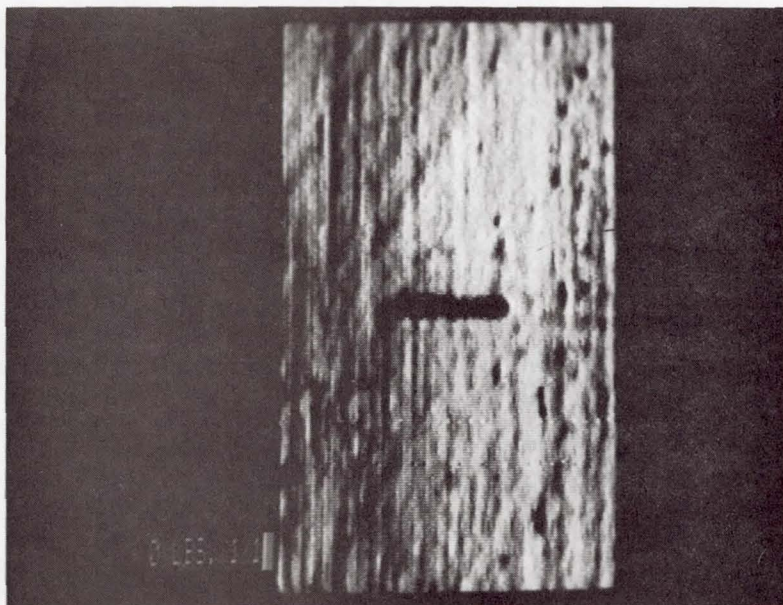


Figure 17. - Tensile loaded specimen: before loading.

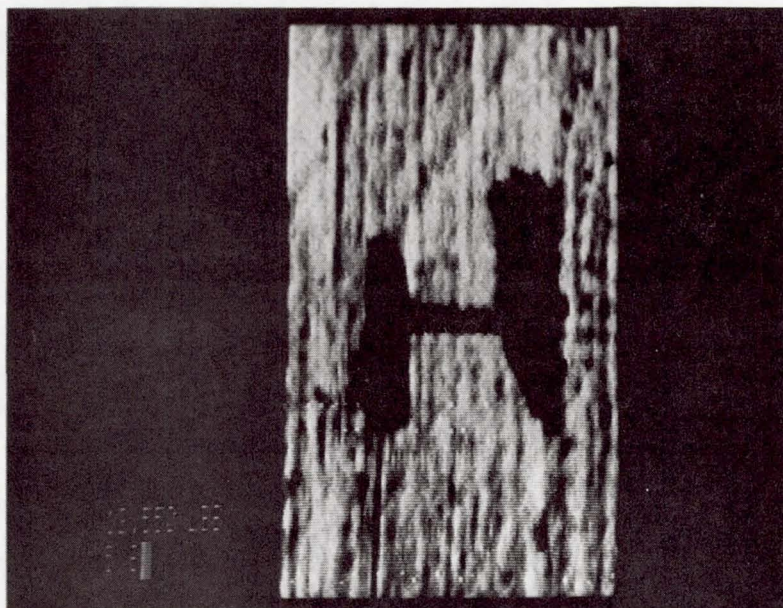


Figure 18. - Tensile loaded specimen: after 12 500 pounds.

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